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**14. ABSTRACT**
The report summarizes the research accomplishments during the first year of the project. Research focused on experimental tasks in support of the development of a multiscale finite element model to be used to simulate blast loading of ocular lenses. Unconfined compression tests and puncture tests were conducted on whole lenses, and imaging of the lens capsule type IV collagen meshwork was attempted by cryo-electron microscropy. Efforts are ongoing for identifying the type IV collagen meshwork structure, and determine material model parameters for the mechanical experiments.

**15. SUBJECT TERMS**
ocular lens mechanical experiments, lens capsule ultrastructure, finite element analysis

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# Contents

# 1 Introduction

In the life of a combat soldier, traumatic cataract in ocular lenses may result from blast loading, whereby (i) the lens capsule (Fig.1) is perforated by intraocular foreign bodies (IOFBs [Walter, 1962, Mader et al., 1993, Parver et al., 1993, Wong et al., 1997, Mader et al., 2006, Weichel and Colyer, 2008]) which in turn damage the lens fiber cells, (ii) the lens is loaded fluid dynamically by the surrounding aqueous and vitreous humors [Banitt et al., 2009] (see Fig.1), and/or (iii) the lens internal substance (crystallins lens fiber cells) is stressed by the passing shock wave. Traumatic cataract can result in a partially or fully clouded lens, complete dislocation of the lens (floating between aqueous and vitreous humors, see Fig.1), or zonule rupture such that partial or full vision loss may occur. The mechanisms of traumatic cataract formation that may require cataract surgery (implantation of an intraocular lens (IOL)) are not well understood in comparison to the mature and ever-improving surgical technology and procedures. The hypothesis of the research is that an ultrastructurally-based computational finite element model of the ocular lens subjected to blast loading can assist in better understanding how traumatic cataract is formed in the combat soldier, and in turn improve our understanding of traumatic cataract in civilians whose eyes are subjected to impact loading. The scope of the research is to develop a multi-scale, ultrastructurally-based, computational model of the ocular lens subjected to blast loading, in conjunction with imaging methods to identify lens capsule and internal substance structure and mechanical experiments for calibrating material model parameters.

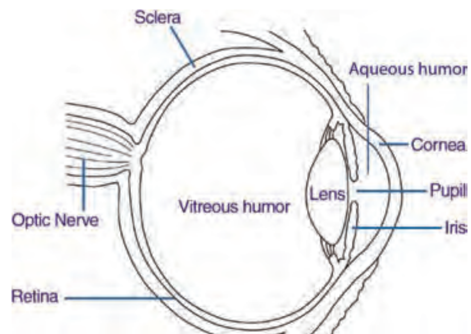

Figure 1. Eye cross-section. `www.nei.nih.gov`.

# 2 Body

**Task 4. unconfined compression testing of whole porcine lenses (0.001 - 1/s strain rate) to estimate whole lens mechanical response and generation of traumatic cataracts at higher strain rates** (months 1-12):

Unconfined compression tests with flat platens were conducted on whole porcine lenses harvested from 2+yr-old and 6-9month old pigs within 36 hours of slaughter. This is necessary to obtain mechanical properties before the lens fiber cells degrade further. Lenses were submerged in balanced salt solution (BSS) at pig body temperature (39.2 °C), and then compressed to 10% and 20% axial strain at 0.1mm/s and 0.3mm/s displacement rates, and then held for $\approx$ 360 seconds to measure the force versus time (i.e., a stress relaxation test). Pre-conditioning cycles were applied to attempt to minimize effects of mechanically testing tissue *in-vitro*. Examples for two lenses from 2+year old pigs compressed to 10% strain at multiple 0.1mm/s rates and holds are shown in Fig.2. The last load and hold curves from Fig.2 are used to fit parameters to a finite strain isotropic viscoelasticity model implemented in a finite element program that can simulate three-dimensional and axisymmetric loading, as shown in Figs.3,4. The lens capsule and lens internal substance are meshed separately, and the geometry of the lens mesh is taken from digital photos, such as in Fig.5. For this age pig, and at these loading conditions, these two eye data

happen to bound the high and low force versus time (stress relaxation) test, with fits for a finite strain isotropic viscoelasticity model shown in Fig.3. The model parameters [Reese and Govindjee, 1998] are determined to be as follows: Eye3 lens capsule ($\tau$ = 10sec, $\mu_{\text{EQ}}$ = 1.275MPa, $\mu_{\text{NEQ}}$ = 0.65MPa, $\kappa_{\text{EQ}}$ = 127.5MPa, $\kappa_{\text{NEQ}}$ = 65MPa), Eye3 lens internal substance ($\tau$ = 10sec, $\mu_{\text{EQ}}$ = 1.275e-4MPa, $\mu_{\text{NEQ}}$ = 6.5e-5MPa, $\kappa_{\text{EQ}}$ = 0.1275MPa, $\kappa_{\text{NEQ}}$ = 0.065MPa), Eye2 lens capsule ($\tau$ = 9sec, $\mu_{\text{EQ}}$ = 0.5175MPa, $\mu_{\text{NEQ}}$ = 0.2MPa, $\kappa_{\text{EQ}}$ = 51.75MPa, $\kappa_{\text{NEQ}}$ = 20MPa), Eye2 lens internal substance ($\tau$ = 9sec, $\mu_{\text{EQ}}$ = 5.175e-5MPa, $\mu_{\text{NEQ}}$ = 2e-5MPa, $\kappa_{\text{EQ}}$ = 0.05175MPa, $\kappa_{\text{NEQ}}$ = 0.02MPa), where $\tau$ is the relaxation time, $\mu_{\text{EQ}}$ the equilibrium shear modulus, $\mu_{\text{NEQ}}$ the non-equilibrium shear modulus, $\kappa_{\text{EQ}}$ the equilibrium bulk modulus, $\kappa_{\text{NEQ}}$ the non-equilibrium bulk modulus. Example images of the lens before and after compression are shown in Fig.5. The remaining data for age range (6-9month and 2+year old pigs) and loading conditions (10% and 20% axial strain, and loading rates 0.1mm/s and 0.3mm/s) are being compiled and will be presented in a near future journal article, along with remaining parameter fits.

Another form of unconfined compression is a puncture test, with image of test and results shown in Fig.6. We are in the process of simulating this experiment using finite element analysis, with viscoelasticity parameters taken initially from the unconfined compression flat platen data, and future perforation modeling of the lens capsule being able to capture puncture. Further puncture tests are being performed on the anterior and posterior sides of the lens.

We are in the process of arranging to have experiments conducted at higher strain rates (1/s) in the soft tissue high strain rate testing laboratory at the Army Research Laboratory, Aberdeen Proving Ground, MD.

**Task 6. imaging of lens fiber cell geometry using confocal laser scanning microscopy (CSLM), and type IV collagen ultrastructure in lens capsule using cyro-electron tomography** (months 1-24):

Figure 7 shows current progress in imaging type IV collagen meshwork of the lens capsule for multiscale finite element modeling of the lens capsule. This figure shows images from applying a cryo-electron microscropy technique, details in a forthcoming paper. The left image shows what appears to be a meshwork structure, which we will be clarifying by a cryo-electron tomography technique. The middle image shows the structure around where the zonules attach to the lens capsule, and the right figure is a higher magnification than in the middle image.

# 3 Key Research Accomplishments

- We have accumulated unconfined compression data for whole porcine lenses at two axial strains (10% and 20%) and displacement rates (0.1mm/s and 0.3mm/s) for estimating finite strain isotropic viscoelasticity parameters. Parameter fits are being completed.
- We concluded that identifying structure of type IV collagen meshwork with cryo-electron microscopy is not sufficient, and thus we are working on using cryo-electron tomography instead.

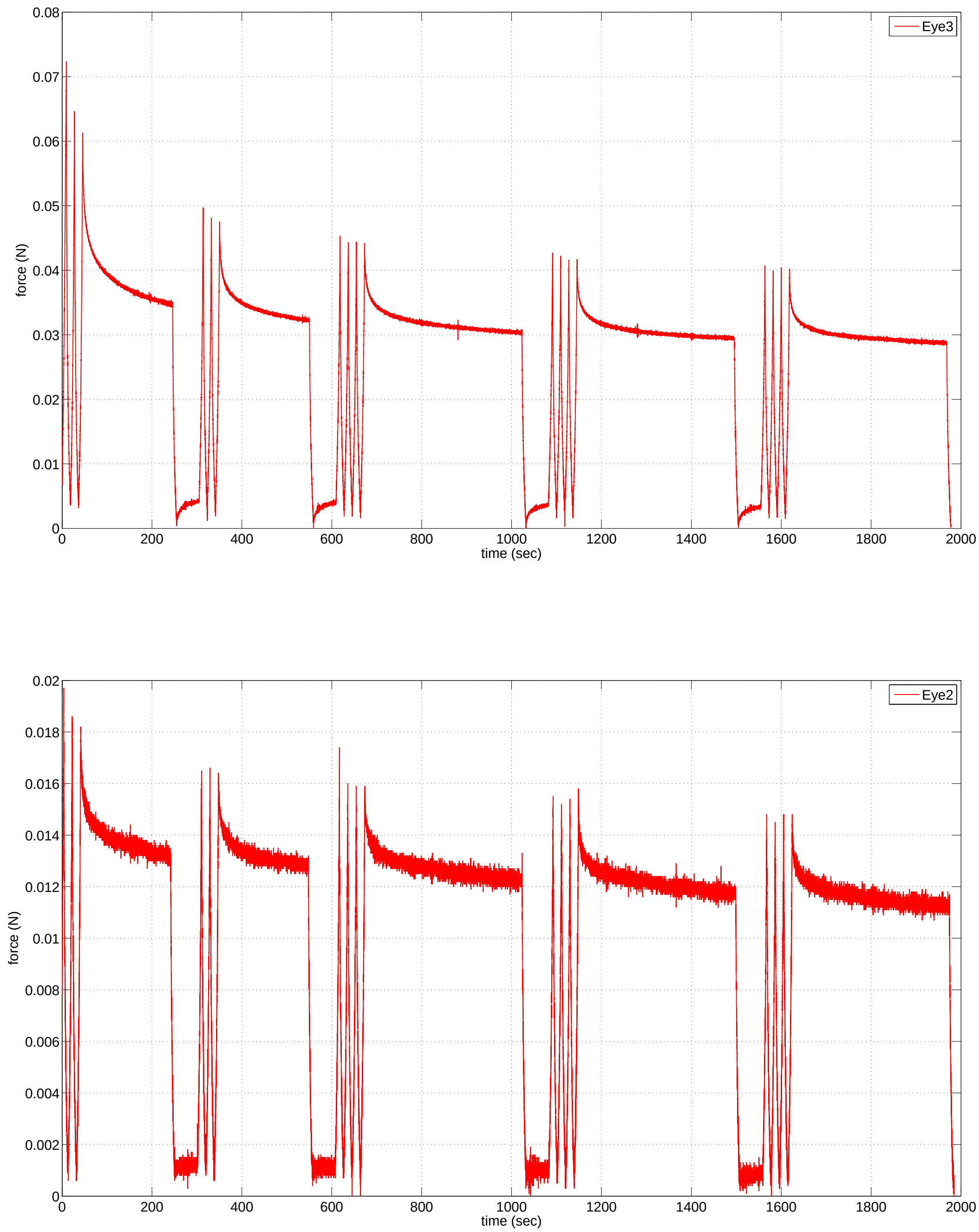


Figure 2. (top) Eye3. (bottom) Eye2.

# 4 Reportable Outcomes

No reportable outcomes yet. Journal papers are in preparation, abstracts for conference posters and presentations are being prepared.

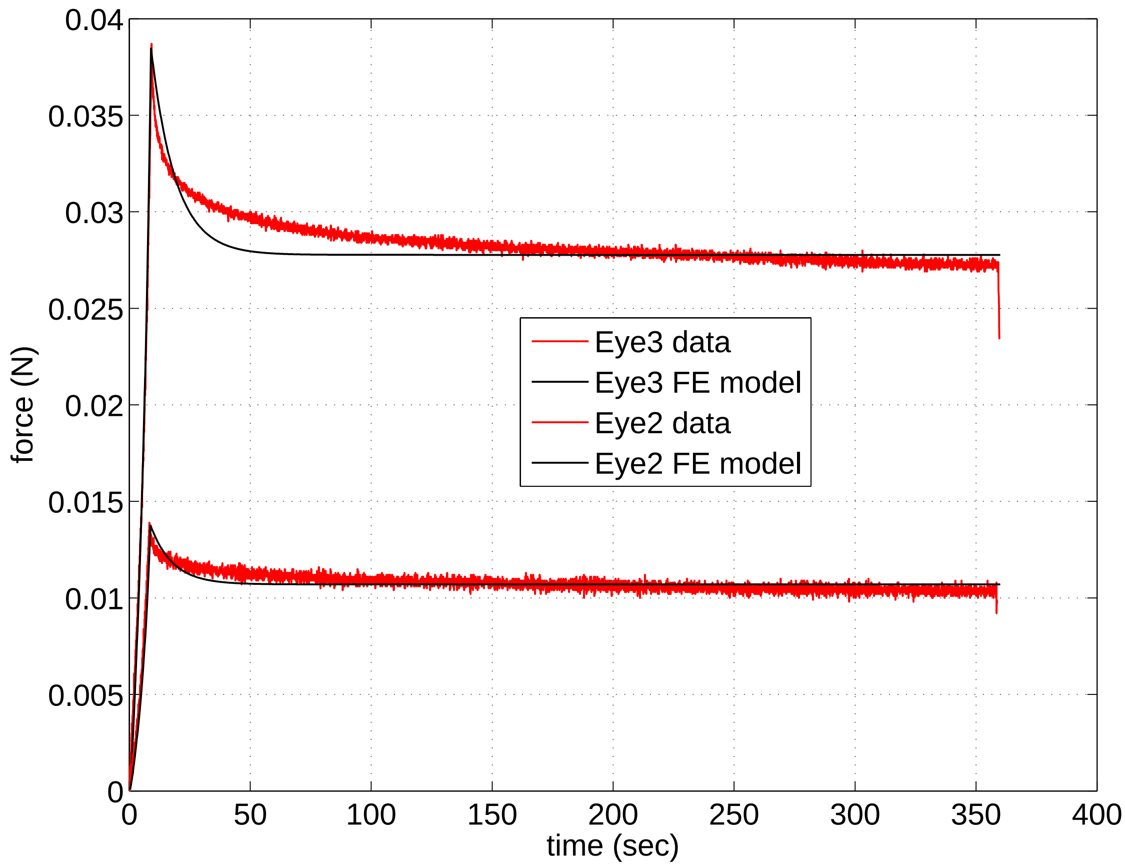


Figure 3. Fit of finite strain isotropic viscoelastic constitutive model in an axisymmetric finite element program, against Eye3 and Eye2 data.

# 5 Conclusion

The research progress to date has focussed on the experimental portion of the research, ranging from unconfined compression with flat platen and puncture tips for estimating material constitutive parameters and puncture resistance, to initial tasks for nanoindentation of lens capsules, and structure identification of the lens capsule using cryo-electron microscopy and tomography. These data and images of structure will provide the basis for multiscale computational finite element models of the ultrastructural response of whole lenses under dynamic loading. Plans are in place for a graduate student to assemble and conduct unconfined compression tests at higher loading rates in the soft tissue high rate materials laboratory at the Army Research Laboratory, Aberdeen, MD. This will fill a gap in our experimental data that we do not have the facilities currently to complete such tests at the University of Colorado, Boulder.

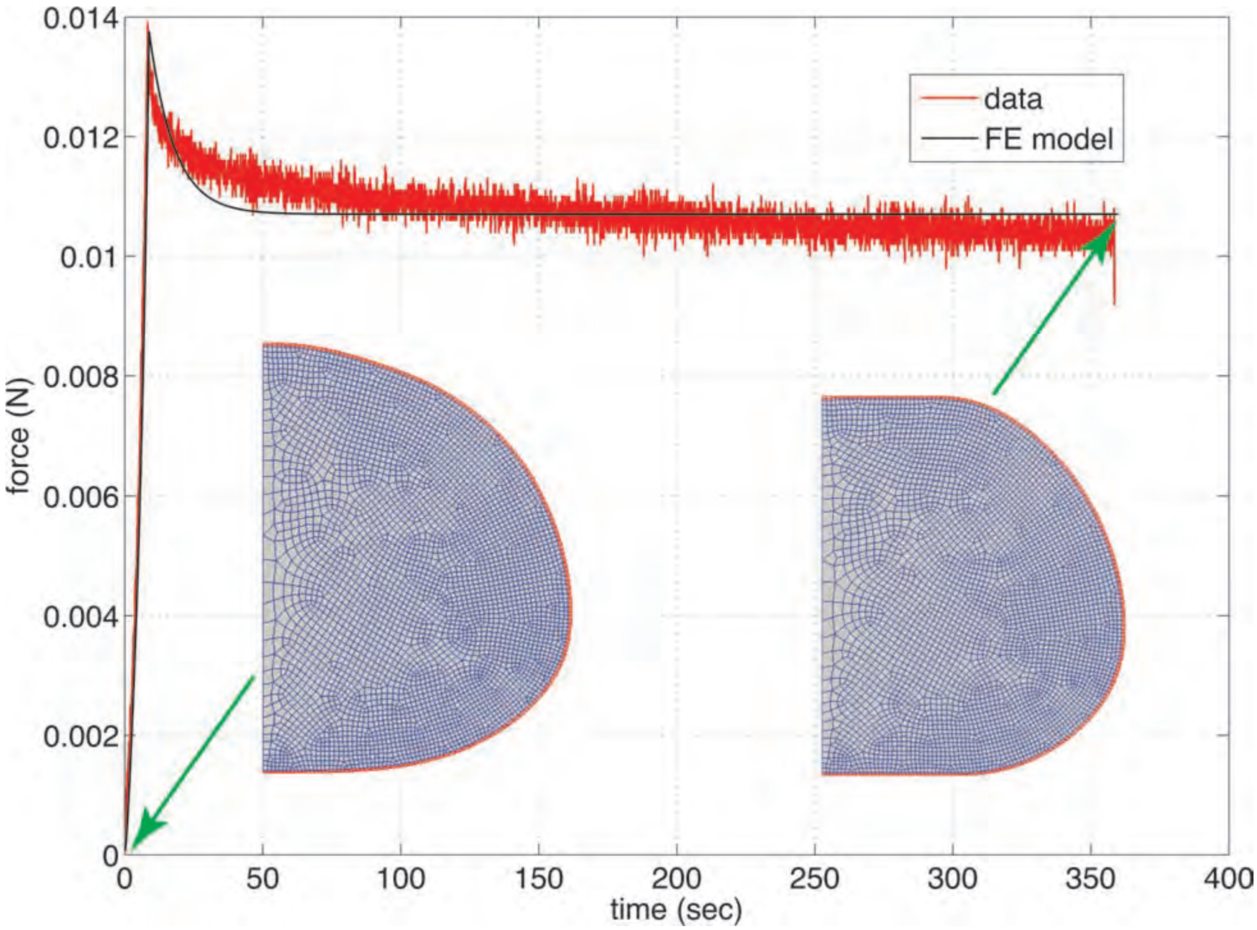


Figure 4. Fit of finite strain isotropic viscoelastic constitutive model in an axisymmetric finite element program, against Eye2 data, also showing undeformed and deformed meshes.

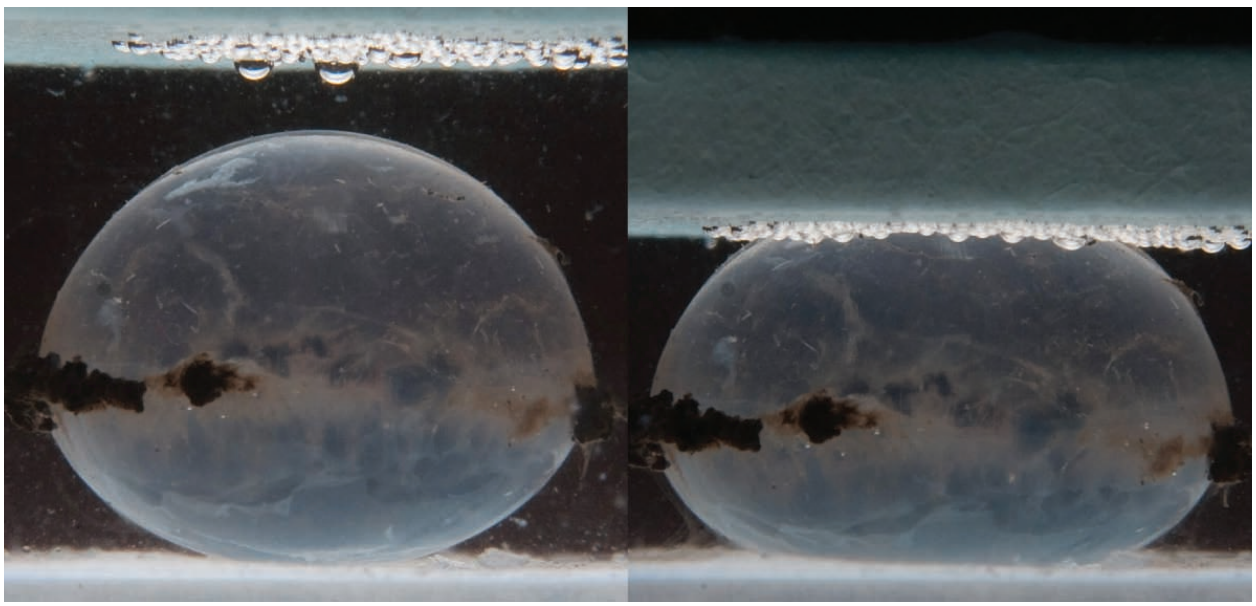

Figure 5. Example images of lens before and after compression to 10% strain during stress relaxation test.

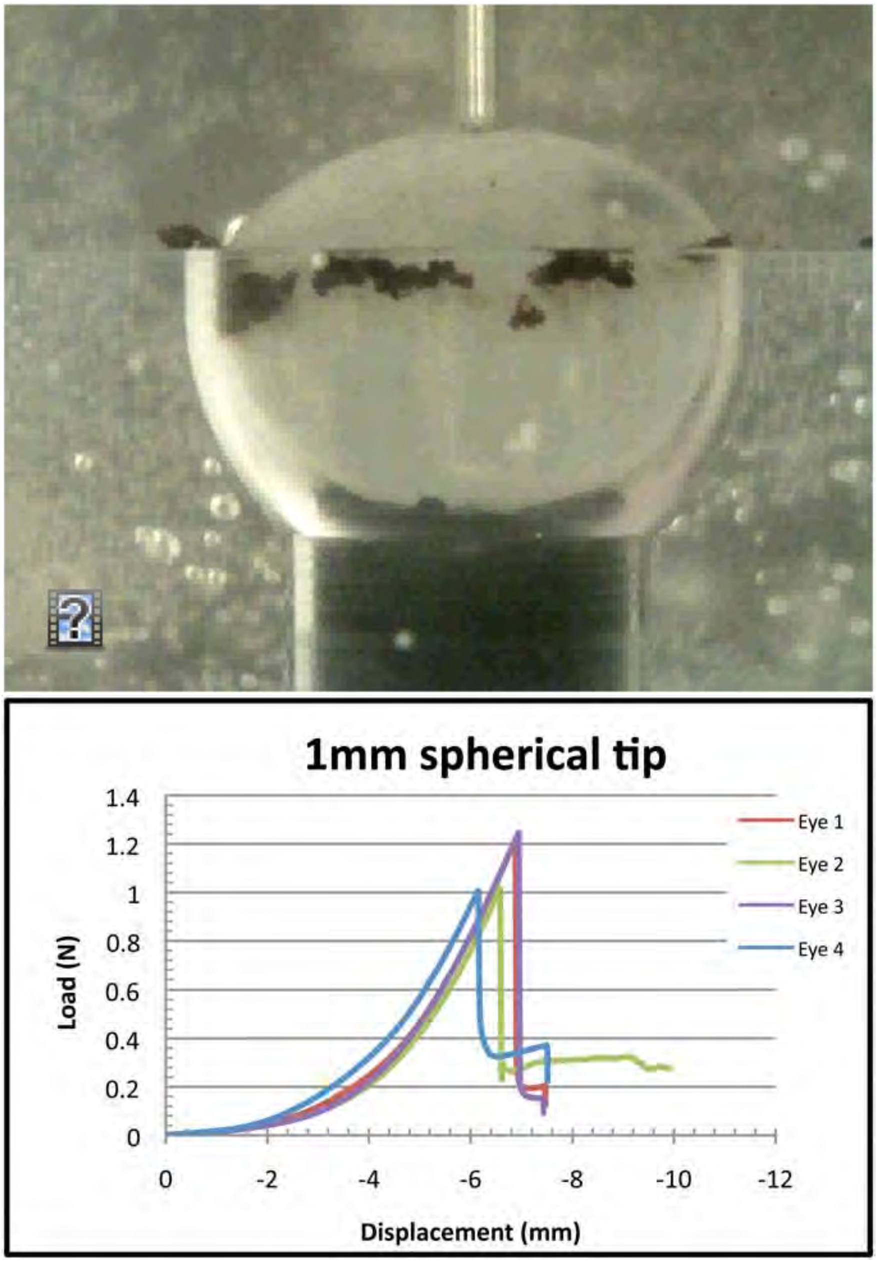


Figure 6. Setup of lens puncture test for estimating penetration strength of lenses, and resulting force versus displacement data. The lenses are cupped with anterior side at the puncture tip. Tests also conducted on posterior side.

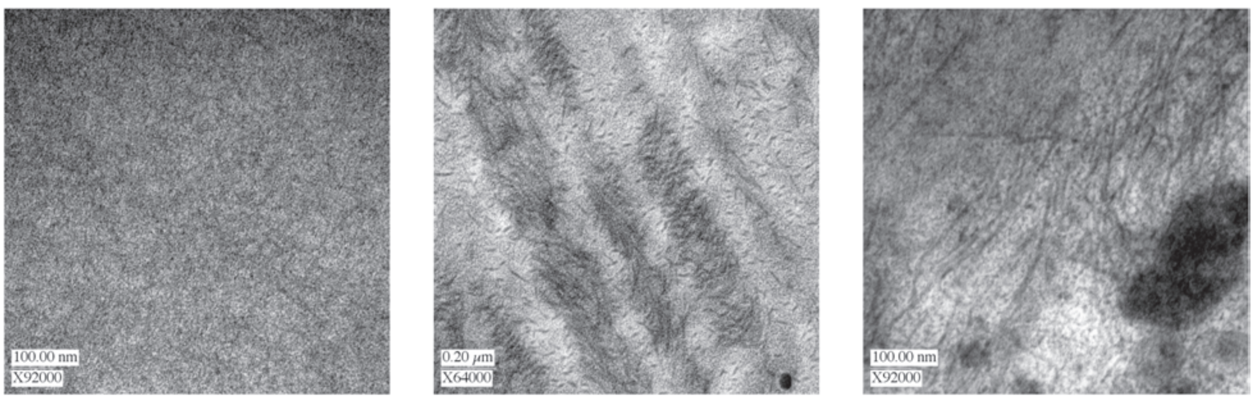


Figure 7. Images of structure in lens capsule via cryo-electron microscropy.

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